REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
Towards predicting Deep Convection in the Labrador Sea

5. FUNDING NUMBERS
N00014-96-1-0573

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
ONR

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
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13. ABSTRACT *(Maximum 200 words)*

We have developed and implemented a method to use real time oceanographic data in conjunction with climatological air-sea flux data to predict the location and strength of deep convection in the Labrador Sea a few weeks in advance. In preparation for this task we have gathered and analyzed a number of historical and recent data sets. In particular the results of a recent mooring deployment during the winter of 1994-1995 gave new insight into the convective process in the Labrador Sea.

14. SUBJECT TERMS
Deep convection, mixed-layer dynamics, Labrador Sea

15. NUMBER OF PAGES
6

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Standard Form 298 (Rev. 2-89)

Final Report for ONR grant:

TOWARDS PREDICTING DEEP CONVECTION IN THE LABRADOR SEA

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Award Number "N00014-96-1-0573"

ABSTRACT

We have developed and implemented a method to use real time oceanographic data in conjunction with climatological air-sea flux data to predict the location and strength of deep convection in the Labrador Sea a few weeks in advance. In preparation for this task we have gathered and analyzed a number of historical and recent data sets. In particular the results of a recent mooring deployment during the winter of 1994-1995 gave new insight into the convective process in the Labrador Sea.

OBJECTIVES

- Inspect historical data from the Labrador Sea and make them available on the web.
- Develop a minimum prediction system to forecast the convective activity several weeks in advance.
- Assess the relative importance of one-dimensional mixing physics versus lateral effects due to mesoscale eddies or mean flows.

APPROACH

The first part of our effort builds on the analysis of historical data. This includes climatologies of oceanic and atmospheric data as well as individual ocean station data and results from pilot experiments during the winter 1994/95. We want to separate a typical mean seasonal cycle from interannual variability for the region. Once that is done we use the data sets do investigate heat, freshwater and buoyancy budgets for the subregions of interest. From those we should be able to estimate lateral flux divergences which then can be used as an additional forcing for the one dimensional prediction system.

The second task is to design a prediction system which can readily incorporate real-time temperature and salinity profiles from profiling ALACE floats (provided by R. Davis and B. Owens) and make use of climatological mean surface flux data. The simplest model will be based on one-dimensional mixing physics and can be used to predict the convective activity at the end of the winter season. This minimal prediction system will then be compared to the observations and also the evolution of dynamical ocean models (in collaboration with J. Marshall).

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK
OFFICE OF PROJECTS AND GRANTS

January 22, 1999
OPG:8952

Dr. Manuel E. Fiadeiro, Program Officer
Office of Naval Research
Attn: Code 322 OM
Ballston Tower One
800 North Quincy Street
Arlington, VA 22217-5000

Re: Final Technical/Patent Report Submission for ONR Award No. N00014-96-1-0573

Dear Dr. Fiadeiro:

In accordance with the terms and conditions of the above referenced grant, we enclose three (3) copies of Final Technical Report and one (1) copy of the completed Final Patent/ Invention Report (form DD-882) for the award entitled "Towards Predicting Deep Convection in the Labrador Sea." The report covers the period of March 1, 1996 to September 30, 1997.

Additional copies of the report have been forwarded as indicated below.

In addition, with respect to the New Technology/Patents Rights clause of the referenced grant, we wish to certify that to the best of our knowledge that there were no reportable items developed under this award.

If you have any questions please contact me at (212) 854-6851 or via e-mail at: alw10@columbia.edu.

Sincerely,

Aleta Walker Boddie
Projects Assistant

AWB/ep

Encl.

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OMB No 9000-0095
Expires July 31, 1995

REPORT OF INVENTIONS AND SUBCONTRACTS

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1a. NAME OF CONTRACTOR / SUBCONTRACTOR: The Trustees of Columbia Univ. in the City of NY

b. ADDRESS (Include ZIP Code): 1210 Amsterdam Avenue, 351 Engineering Terrace, MC 2205, NY, NY 10027

c. CONTRACT NUMBER: N00014-96-1-0573

d. AWARD DATE (YYMMDD): 96/03/01

2a. NAME OF GOVERNMENT PRIME CONTRACTOR: same

b. ADDRESS (Include ZIP Code): same

c. CONTRACT NUMBER: same

d. AWARD DATE (YYMMDD): same

3. TYPE OF REPORT (X one): a. INTERIM X b. FINAL

4. REPORTING PERIOD (YYMMDD): a. FROM 96/03/01 b. TO 97/09/30

SECTION I - SUBJECT INVENTIONS

5. "SUBJECT INVENTIONS" REQUIRED TO BE REPORTED BY CONTRACTOR / SUBCONTRACTOR *(If "None," so state)*

NAME(S) OF INVENTOR(S) (Last, First, MI) a.	TITLE OF INVENTION(S) b.	DISCLOSURE NUMBER, PATENT APPLICATION SERIAL NUMBER OR PATENT NUMBER c.	ELECTION TO FILE PATENT APPLICATIONS d. (1) UNITED STATES (a) YES	(1) UNITED STATES (b) NO	(2) FOREIGN (a) YES	(2) FOREIGN (b) NO	CONFIRMATORY INSTRUMENT OR ASSIGNMENT FORWARDED TO CONTRACTING OFFICER e. (1) YES	(2) NO
NONE								

f. EMPLOYER OF INVENTOR(S) NOT EMPLOYED BY CONTRACTOR / SUBCONTRACTOR

(1) (a) NAME OF INVENTOR (Last, First, MI)

(b) NAME OF EMPLOYER

(c) ADDRESS OF EMPLOYER (Include ZIP Code)

(2) (a) NAME OF INVENTOR (Last, First, MI)

(b) NAME OF EMPLOYER

(c) ADDRESS OF EMPLOYER (Include ZIP Code)

g. ELECTED FOREIGN COUNTRIES IN WHICH A PATENT APPLICATION WILL BE FILED

(1) TITLE OF INVENTION

(2) FOREIGN COUNTRIES OF PATENT APPLICATION

SECTION II - SUBCONTRACTS (Containing a "Patents Rights" clause)

6. SUBCONTRACTS AWARDED BY CONTRACTOR / SUBCONTRACTOR *(If "None," so state)*

NAME OF SUBCONTRACTOR(S) a.	ADDRESS (Include ZIP Code) b.	SUBCONTRACT NUMBER(S) c.	DFAR "PATENT RIGHTS" d. (1) CLAUSE NUMBER	(2) DATE (YYMMDD)	DESCRIPTION OF WORK TO BE PERFORMED UNDER SUBCONTRACT(S) e.	SUBCONTRACT DATES (YYMMDD) f. (1) AWARD	(2) ESTIMATED COMPLETION
NONE							

SECTION III - CERTIFICATION

7. CERTIFICATION OF REPORT BY CONTRACTOR / SUBCONTRACTOR (Not required if: Small Business or Non-Profit organization.) (X appropriate box)

a. NAME OF AUTHORIZED CONTRACTOR / SUBCONTRACTOR OFFICIAL (Last, First, MI): Lucas, Barbara L.

b. TITLE: Senior Projects Officer, OPG

c. I certify that the reporting party has procedures for prompt identification and timely disclosure of "Subject Inventions," that such procedures have been followed and that all "Subject Inventions" have been reported.

d. SIGNATURE: Barbara Lucas

e. DATE SIGNED: 99/01/22

N/A = Not Applicable

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WORK COMPLETED

We have gathered and inspected most of the historical data and made them available on the web. The mean seasonal cycle and the interannual variability have been computed and we are now inspecting regional budgets. A first estimate of the lateral heat flux divergence was determined using data from a pilot mooring deployment and the findings are prepared for publication in collaboration with P. Rhines, J. Lazier and others.

From November 1996 until early March of 1997 we have made experimental predictions for the expected maximum convective activity of the central Labrador Sea. Those predictions were used in combination with historical data to fine tune the winter cruise schedule. In particular the decision of where to deploy the convection floats was influenced by our predictions.

During the last few month we have set up a dynamical ocean model for the North Atlantic region and are currently preforming sensitivity studies using different parameter choices, initial conditions and surface forcing data sets.

RESULTS

One of the key questions in order to better understand and predict the deep convective activity in a basin such as the Labrador Sea is:
How strong is the lateral transfer of heat freshwater and hence buoyancy?
This quantity is important is two ways. Firstly, if there were no lateral flux of properties the newly ventilated deep water would not leave the region and hence would only insignificantly contribute to the ocean ventilation. Therefore it is directly related to the overall deep water formation rate of the basin. Secondly, the lateral transfer of heat and freshwater will influence the local stratification and thereby influence the vigor of deep convection for the next winter season. The inspection of surface heat flux data sets and annual time series of heat content in the central Labrador Sea yielded an annual mean lateral heat flux divergence which is equivalent to an annual mean heat loss of 50-100 W/m^2. The vertical structure of that heat flux is equally important and decays strongly with depth. About 50% of the lateral flux divergence was found to be in the upper 200 m of the water column. We are currently performing a similar analysis for the fresh water flux divergence.

The second important result was that it is feasible to perform real-time predictions of the expected deep convective activity. The first trial for the prediction system based on the simplest possible balance has proven to be useful. We made use of real-time temperature and salinity data from profiling ALACE floats with a delay of about one-two weeks. The predictions based on this simple system gave consistently a maximum depth of the deep convective activity of about 800 m which turned out to be close to the observed value during the winter cruise in March 1997. As an example figure 1 shows one of this maps where we also included a hand drawn diagnostic of where the convection might be deepest.

The first trials using a more complete three-dimensional dynamical model have shown that it is harder to overcome model shortcomings such as to much diffusion and to weak advection within the boundary currents. However, those simulations might still be the way to go once we have a better understanding of the fundamental problems.

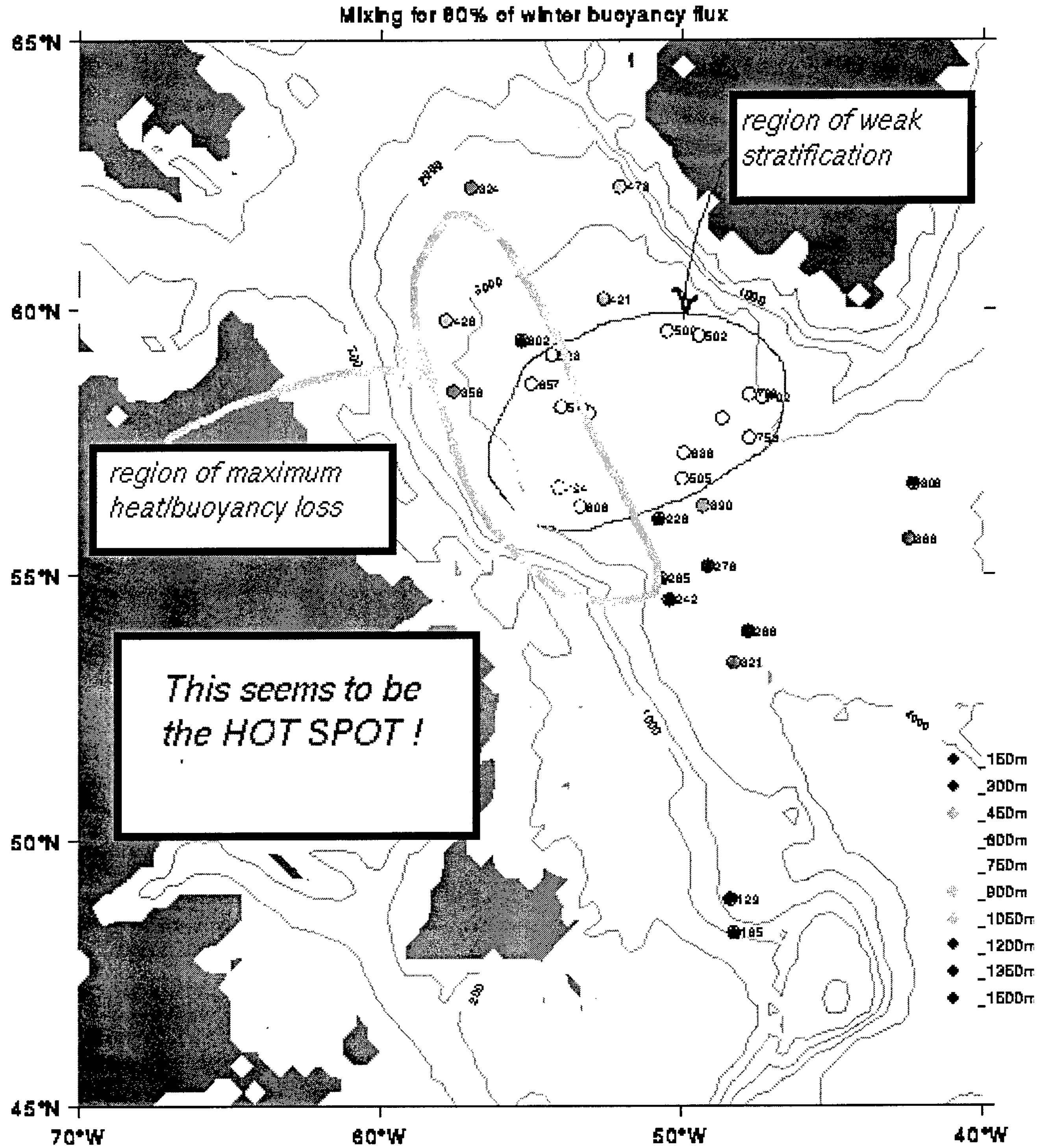

Figure 1: Prediction of the expected mixed layer depth using the PALACE float stratification (thanks to R. Davis) and a climatological forcing. Based on this information we pointed to a region where the chances for deep convective mixing were maximum.

APPENDIX:

A1: DETAILS of the prediction scheme developed:

We have made use of the buoyancy conservation equation:

$$\int B_0 \, dt = B(zmix) = g/\varrho_0 \int_{zmix}^{0} \sigma(zmix) - \sigma(z) \, dz$$

which relates the air sea flux of buoyancy flux *Bo* (dependent on the heat (Q) and freshwater flux (E-P)) to the density profile given by ó(z) at the initial time. If the convective process is to first order non-penetrative and the nonlinearities of the equation of state can be ignored the right hand side gives the amount of buoyancy that needs to be released in order for convection to penetrate to a depth *zmix*. This is the simplest possible description of the one dimensional convective process. The skill of such a form is limited because all lateral flux divergences are assumed to be small when compared to the air-sea flux. One might expect that during a vigorous winter month this is largely true but over the course of a whole season the lateral flux divergences need to be as large as the time averaged air-sea flux if the ocean is in some sort of steady state.

We have used historical data to test these assumptions and found that the associated errors are not bigger compared to the uncertainty in the air-sea flux. Because of that we decided to use this very simple system for our experimental prediction efforts.

For a typical prediction we would use the real time temperature and salinity profiles as given by the PALACE floats to obtain a density profile. From the density profile we would then calculate the "initial" buoyancy *B* as a function of depth. Note that this procedure only requires the float data to be accurate as a function of depth. Any slow sensor drift, as it was found to be the case for salinity, would only marginally affect the calculation of *B*.

Once we have obtained all the "initial" buoyancy profiles we compute the expected time integral of the air-sea buoyancy flux *Bo*. We have used the heat and fresh water flux as given by the COADS data to compute the air-sea buoyancy flux as a function of space. Those time series were then integrated between the 1. December and the end of March to give a reference value.

The final predictions step was to use a fraction of the integrated buoyancy flux (100% for a prediction between 1. Dec - end March) and find the corresponding ocean mixed-layer depth *zmix,* where the time integrated air-sea buoyancy flux was equal to the "initial" buoyancy. We then display the mixed-layer depth graphically and publish the maps on the web.

A2: PROBLEMS with the MICOM ocean model:

We have carried out preliminary studies by adapting the the Miami Isopycnal Coordinate Model (MICOM) to a Labrador Sea model domain. The MICOM model is described by Bleck (1997) and in brief it consist of a series of vertically stacked isopycnal layers. The topmost layer describes a mixed layer of arbitrary density and hence is non-isopycnal. The flow field and thickness of each layer is obtained by solving an appropriate shallow water equation for each layer. The model is forced by heat, freshwater, and momentum fluxes at the surface.

We uncovered some difficulties with the present version of MICOM that made it unsuitable for our particular application to the convective gyres of the Labrador Sea. While no model is ideal for all applications we now point out the particular shortcomings we experienced with MICOM.

First, the isopycnal framework is ideally suited to regions of strong density gradient such as ocean fronts but is less suited to regions of low stratification such as convective zones because by definition one has very poor vertical resolution in the model in such locations. For instance, if we define the model vertical space to span say ten isopycnal layers with a density range representing that of waters found in the subpolar gyre then as the model integrates forward in time and convection sets in we find that we end up with only one or two layers actually containing water in the Labrador Sea while the remaining layers in the Labrador Sea are evacuated and not used because water of their density class is not present.

Secondly, the present MICOM advects salinity but diagnoses temperature on isopycnal layers. The reason this can be done is that the layers are isopycnal and hence prognosing one thermodynamic variable should suffice. This approach, however, ignores the cabelling effect which can be important for cold oceans where the equation of state is most nonlinear. The result of advecting salinity and then inverting the equation of state to diagnose the potential temperature led us sometimes to unrealistic temperatures. Another failing of this approach is that it does not conserve heat energy. The solution to this problem is to advect both temperature and salinity. This will cause the pre assigned and fixed layer density values to drift which then must be corrected by using a diapycnal flux scheme to restore layer densities to their proper values. MICOM has recently adopted a diapycnal scheme and thus in future should be able to properly treat both thermodynamic variables.

Thirdly, the smooth implementation and functioning of an embedded surface mixed layer model into an isopycnal model is complicated by a well-known difficulty concerning mixed layer detrainment. The crux of the problem is that since the mixed layer is of arbitrary density, while the isopycnal layers are of fixed values, and when a detrainment event occurs and water must be injected from the mixed layer into some deeper isopycnal layer the waters of the mixed layer that are being detrained will not in general match any of the pre assigned isopycnal coordinates. MICOM has implemented a splitting scheme that partially alleviates this problem by dividing up the detrained mixed layer water into an amount that exactly matches the density of the next layer below the mixed layer and an amount which is then rejoined to the mixed layer. This splitting is a

violation of entropy as well as resulting in incomplete detrainment.

REFERENCES

Most of our work can be found on the web under
http://www.ldeo.columbia.edu/~visbeck/labsea

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